Pre-, Intra-, and Postoperative Use of Dynamic Infrared Thermography (DIRT) Provides Valuable Information on Skin Perfusion in Perforator Flaps Used in Reconstructive Surgery

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ABSTRACT

A perforator flap is a piece of skin and subcutaneous (fatty) tissue that is transferred from one part of the body to another in the same person - so called autologous transplantation. In plastic surgery, perforator flaps are often used to reconstruct or to close defects due to trauma, tumor resection, and pressure sores. A transplanted perforator flap relies on its blood supply from one artery and one vein, so-called perforating blood vessels. During surgery, these vessels are reconnected to blood vessels at the site of the defect using microsurgical techniques since the vessel caliber is often only 1 to 2 mm. There are three phases in free perforator flap surgery - the preoperative, intraoperative, and postoperative phase. In the preoperative phase, the surgeon has to select a suitable perforator that can perfuse the flap. The variability in the vascular anatomy, the distribution and size of perforators makes this rather challenging. In the intraoperative phase the successful reconnection of the blood vessels is a critical point and the tiny perforator may easily become damaged and as a result the blood supply to the flap may become impaired. Postoperative monitoring of flap perfusion is also important since early recognition of impaired perfusion allows early intervention and prevention of partial or total flap failure.

A simple and reliable imaging technique that helps the surgeon to select the most suitable perforator (pre-operative phase), as well be able to evaluate blood perfusion in flaps both intra- and post-operatively, would be very beneficial. During the last 5 years, we have successfully employed dynamic infrared thermography (DIRT) in all three phases of perforator flap surgery. The DIRT technique involves observing changes in temperature as well as the temperature distribution in an area of interest following a thermal challenge. By applying a thermal challenge, the subsequent recovery of the skin temperature towards its thermal equilibrium is evaluated. In practice, the skin area being examined is subjected to a thermal stress by fan cooling or by applying cold objects to the skin surface. The thermal images can be analyzed with respect to the rate and thermal pattern of recovery, both of which are dependant on the amount of blood perfusing the flap. By using DIRT in our studies, we have been able to improve the surgical outcome of perforator flaps.

INTRODUCTION

A perforator flap is a piece of skin and subcutaneous tissue that is transferred from one part of the body to another in the same person (autologous transplantation). The vessels that supply blood to the flap are called perforators. Each perforator consists of one artery and one vein. A perforating artery, which is a branch of a larger vessel located in the deeper tissues, eventually courses all the way up to the skin. On its route to the skin, the perforator artery passes, in some cases, in between muscles and, in other cases, through a muscle before it perforates the overlying fascia (layer of fibrous tissue separating the skin and fatty tissue from the underlying muscle). Thus, the term “perforator” relates to the fact that the vessel perforates the fascia. From here, it courses through the subcutaneous tissue to the skin. While some perforators have many side branches, others perforators have only a few, coursing their way directly to the skin (Figure 1). These perforating blood vessels are not very large, only having a diameter of a few (1 or 2) millimetres. In plastic surgery, perforator flaps are often used to reconstruct or to close large defects caused by trauma, tumour resection, and pressure sores. The work by Manchot (1889), Salmon (1936) and Taylor (1987) has greatly contributed to our understanding of the vascular anatomy of the skin. Over 300 perforators have been identified that are spread all over the human body although there is a large variability in the distribution, number, and caliber of perforators for each anatomical area. In plastic and reconstructive surgery, perforator flaps have become increasingly popular during the last two decades. Their main advantage is that they do not include a muscle or fascia, thereby resulting in fewer post operative complications.

Earlier, it was thought necessary to include a muscle or fascia to guarantee the blood supply to the skin and subcutaneous fat, the advantage being that by including a muscle or fascia a large number of perforators were included. However, Koshima and Soeda (1989) demonstrated that a large piece of skin and subcutaneous fat from the lower abdomen could actually survive on only one tiny perforator. It is, however, crucial for survival of this tissue that the perforator has a good calibre. As mentioned before, there is for each anatomical area, a large variability in the distribution, number, and calibre of the perforators. Before one can harvest a perforator flap, it is important to have knowledge of the location of the most suitable perforator that will be used to perfuse the flap. Considering that tissue flaps in excess of 1 kg are often used in reconstructive surgery, it is obvious that the preoperative selection of a perforator –which will have the task of adequately supplying blood to the entire flap on its own—is critical to the survival of the transplanted flap of tissue.

Today, there are several imaging technologies available for the pre-operative identification of suitable perforating vessels for tissue transfer including Color Doppler ultrasound techniques as well as radiographic techniques such as multidetector CT (MDCT) angiography. Although the color Doppler ultrasound technique is very accurate in locating a suitable perforator, the examination may take up to 1 or 2 hours and is, in addition, very operator-dependent. The use of MDCT angiography is considered by many the "gold standard" in the preoperative mapping of perforators. This technique provides adequate information on the location, calibre, and course of the perforator artery. The use of this technique requires the use of ionizing radiation and intravenous contrast.

During the operation, the perforator has to be dissected free from the surrounding tissue. Only the preoperatively selected perforator is left intact, while all other perforators that normally contribute to the perfusion of the tissue are cut and sealed. The remaining uncut perforator, consisting of one artery and vein, is also called a pedicle. This pedicle ensures that the flap is still being supplied with blood (Figure 1). The perforator flap can be used to close or to restore a defect in close vicinity to the area where the flap has been harvested. In such a case, the pedicle can be left intact. In free perforator flap surgery, on the other hand, the pedicle has to be cut to enable the transfer of the flap to a defect at a longer distance. After the flap has been transferred, it is crucial for survival of the flap that the blood supply to the flap is re-established. Both the artery and the vein of the pedicle of the flap are re-connected (anastomosed) with the use of a microscope and microsurgical techniques to an artery and vein at the defect site in order to re-establish the blood supply to the flap.

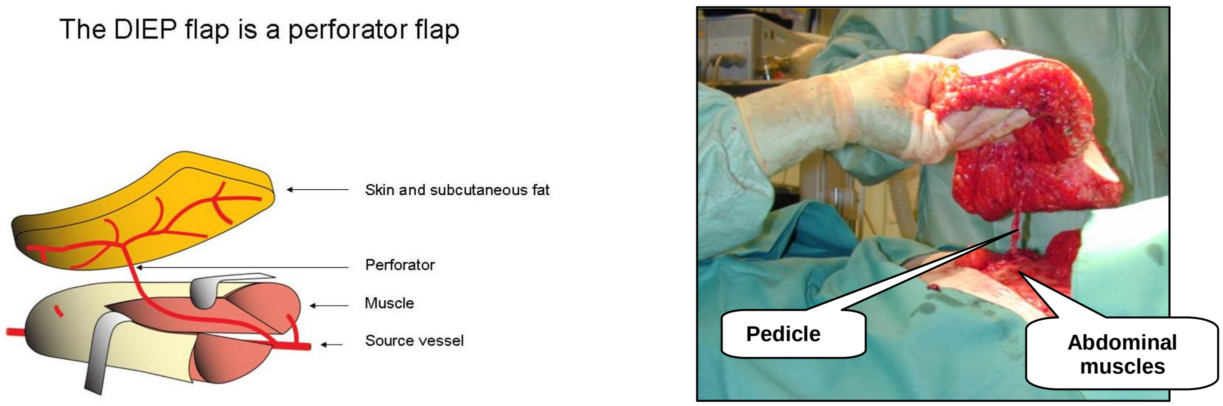

Fig. 1. *The schematic picture on the left demonstrates the principle of a perforator flap. The flap receives its blood supply from a perforator that passes through muscle and emerges from the source vessel that lies underneath the muscle. The photograph on the right shows a harvested abdominal flap (skin and fat tissue). The pedicle, which includes a perforating artery and vein, can be seen emerging from the underlying abdominal muscles.*

After the vessels have been connected, the flap will under normal circumstances become perfused with blood. The surgeon may be able to observe the reperfusion by a change in color or by bleeding from the edges of the flap. This requires, however, considerable experience. Problems with the connection of the vessels can cause an impaired arterial inflow or venous outflow. Suturing the flap into place may cause kinking, compression, or torsion of the pedicle and eventually lead to impaired perfusion of the flap, even to partial or total flap loss. There are currently no techniques that can provide the surgeon with continuous and real-time information of flap perfusion intraoperatively. Such a technique would be of enormous benefit as it would allow for instantaneous action by the surgeon when impaired perfusion occurs.

In the postoperative phase, it is important to monitor the perfusion status of the flap. If there are signs of arterial inflow or venous outflow problems, the patient should be re-operated as soon as possible. Early surgical re-intervention has shown that flaps can be salvaged. Clinical observation of color, turgor, and temperature is the most frequently used monitoring technique during the first postoperative days. The first days after surgery are particularly critical as circulatory problems appear to develop within the first 72 hours after the operation.

During the last 5 years, we have been using dynamic infrared thermography (DIRT) in all three phases of perforator flap surgery (de Weerd et al, 2006; 2009). Our studies have been a great help in improving the surgical outcome as well as improving our understanding of the perfusion physiology of perforator flaps. In this article we will describe the use of infrared thermography in so-called free perforator flap surgery by using the reconstruction of the female breast in patients who have previously lost a breast as a result of cancer surgery as an example.

THE DIEP FLAP AS A MODEL IN FREE FLAP SURGERY

Autologous breast reconstruction has become an integrated part in the overall treatment for breast cancer patients scheduled for mastectomy (removal of a breast). Many studies have demonstrated the psychological, cosmetic, and sexual benefits of post-mastectomy breast reconstruction. There are several ways to reconstruct a new breast. The use of the free Deep Inferior Epigastric Perforator (DIEP) flap, in which skin and subcutaneous tissue from the lower abdomen is transferred to the thoracic wall, has become an increasingly popular method for breast reconstruction after surgical treatment for breast cancer. Patients treated with this technique are especially pleased with the natural shape, soft consistency, and permanency of the aesthetic result.

The DIEP flap receives its blood supply from a perforator that arises from a source vessel called the deep inferior epigastric artery and vein. This source vessel lies under the muscle of the lower abdominal area. There are several perforators arising from the deep inferior epigastric system. During the preoperative planning, it is important to select only the most suitable perforator to guarantee adequate perfusion of the flap. The other perforators are cut and sealed. Finally, the “selected” perforator in its pedicle will also be cut when the flap is transferred from the lower abdomen to the thoracic wall. During this period, there will be no blood flow in the flap (Figure 2). The microsurgical reconnection of blood vessels at the thoracic area is time-consuming and during this time period, the flap can be without any blood supply for as much as an hour.

After transfer, re-establishing blood circulation in the flap is a crucial step in the operative procedure. In this case, the vessels of the flap are anastomosed to the internal mammary vessels on the thoracic wall. This connection, called the microvascular anastomosis, is the most critical procedure during the operation. Normally, clinical monitoring of flaps relies on skin colour, capillary refill, and turgor to provide visual evidence of flap perfusion. Recognising the visual cues of a failing flap early enough to successfully salvage the tissue requires considerable clinical experience. A number of monitoring techniques have been devised to facilitate the early detection of poor flap perfusion, allowing prompt surgical intervention where necessary. However, the use of these monitoring techniques is restricted to the postoperative phase and they cannot easily be used during the operation. Salmi et al (1995) were the first to report the use of infrared thermography for post-operative monitoring of free flaps. The Department of Plastic Surgery at the University Hospital of North Norway has a leading position in breast reconstruction in Norway. In this article, we will describe how dynamic infrared thermography can be used not only for post-operative monitoring of flap perfusion, but can also provide valuable information to the surgeon both pre-and intra-operatively.

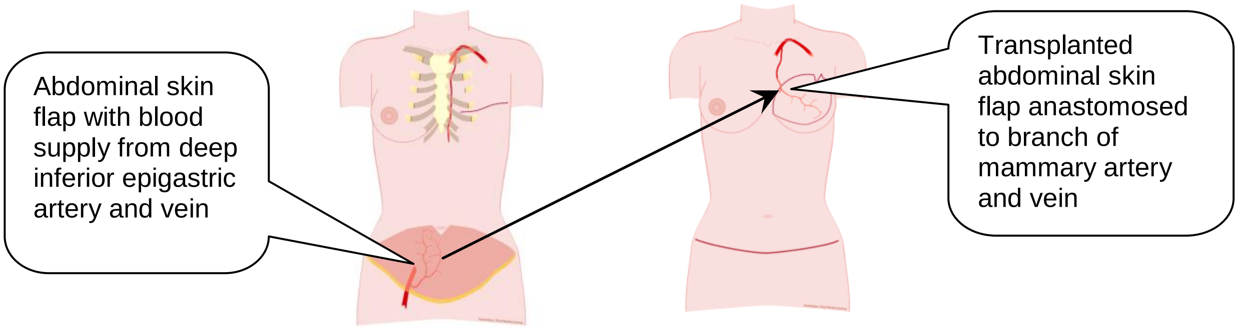

Fig. 2. *Schematic diagram describing concept of autologous breast re-construction.*

PRE-OPERATIVE USE OF DIRT

Meticulous planning during the preoperative phase is a prerequisite for successful perforator flap surgery. The surgeon has to make an exact evaluation of the total volume of subcutaneous tissue needed to allow for the reconstruction of an aesthetically-pleasing breast. Some patients are reluctant to have a reduction of the remaining healthy breast. In these cases, it may be necessary to harvest a flap as large as possible from the lower abdomen to match the other breast. As mentioned, only one of the many perforating blood vessels supplying the skin and underlying fatty tissue will be selected and carefully dissected out during the preparation of the abdominal flap prior to transfer and reconstruction of the new breast. All the other vessels are cut and sealed. The key issue during the preoperative phase is to select the most suitable perforator to perfuse the flap. While there are several complex imaging techniques available such as multi detector computer tomography (MDCT), these are costly and often involve exposing patients to radiation. Our studies revealed that dynamic infrared thermography (DIRT) provides a good alternative method for the preoperative selection of suitable perforators

The technique we use is quite simple. It is based on the fact that the most powerful perforators transport heat from the deeper warmer tissue to the skin surface. The locations of perforators can be observed on the abdominal skin surface with the infrared camera as hot spots. In order to identify such hot spots, we deliver a cold challenge to the exposed abdominal area by blowing air at room temperature over the abdomen for a period of 2 minutes using a desk top fan. The examination takes place in a special examination room with a room temperature of 22-24°C, constant humidity, and air circulation. The fan cooling causes a general cooling of the abdominal skin that is well within the physiological range. Following cessation of cooling the abdominal skin rapidly rewarms on its own. Here we continuously monitor the rate and pattern of rewarming which with an IR camera. This is a key point of the whole examination. The strongest perforators can be identified as the most rapidly returning hot spots (Figure 3).

During a DIRT examination, differences in the rate and pattern of rewarming between hot spots became apparent. Hot spots with a rapid rewarming appeared as bright hot spots on the thermal image. These hot spots were all associated with an arterial sound that could be heard with the aid of a small handheld Doppler device (a non-invasive method to measure the microcirculatory blood flow in, for example, the skin, based on the fact that light impinging any moving scattering object undergoes a very small frequency shift, known as the Doppler effect). The brightness of the hot spot was positively correlated to the volume of the audible Doppler signal. The results from the analysis of the DIRT examination revealed a large variability in the number and position of hot spots between the left and right side of the abdomen in an individual patient. There was also a large variability in the number and position of hot spots between different patients. With the

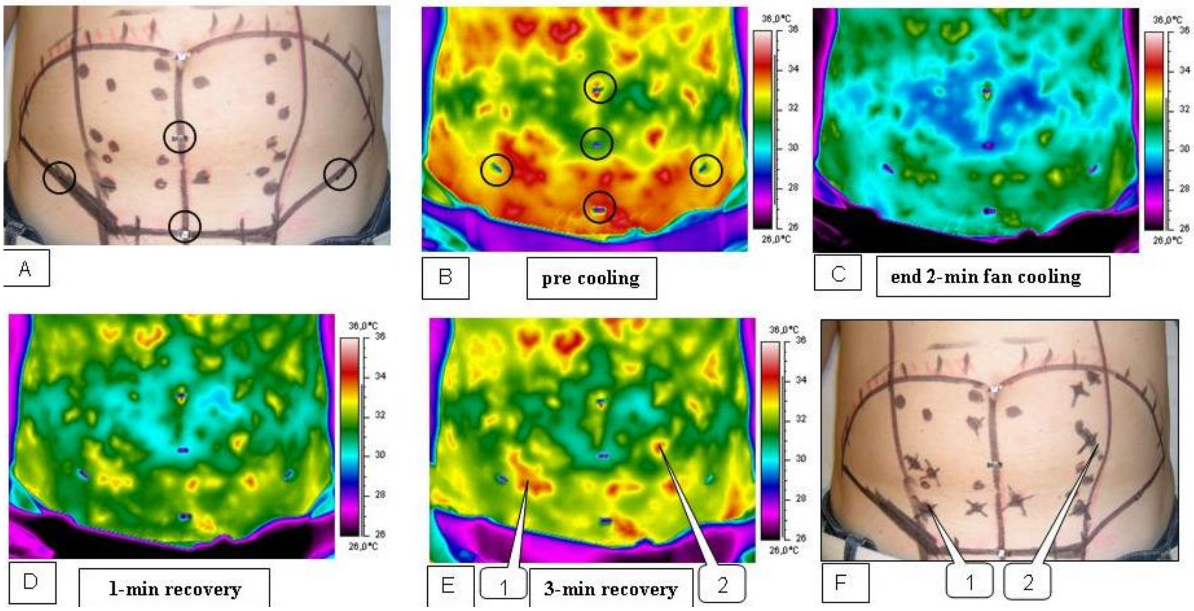

Fig. 3. A: photograph of lower abdomen. The 4 black circles mark the location of small pieces of metal tape used as reference points in the IR images. B. IR thermal image prior to abdominal cooling. C: IR thermal image at end of 2 min cooling period. Following the abdominal cooling the skin temperature rapidly rewarms (D and E). The locations of two strong hot spots are indicated in E. In panel F each black spot marked with an X indicated where a strong arterial sound can also be heard at the hot spot with a Doppler ultrasound instrument.

experience we have gained using DIRT in preoperative planning over the last few years, we have come to the conclusion that the identification of a suitable perforator needs to fulfil the following criteria:

1. A rapidly appearing hot spot after the cold challenge
2. This hot spot is associated with an audible Doppler sound
3. The perforator is not located at the edge of the flap

In a few patients, we also performed MDCT scans. All the perforators as selected from the DIRT examinations could be related to a clearly visible perforator on the MDCT scan.

INTRA-OPERATIVE USE OF DIRT

After the flap has been harvested from the abdominal area, it is without any blood perfusion for a period of time before the vessels are connected to the mammary vessels. During this time period which may be as much as an hour, the non-circulated flap cools down. Following completion of the microsurgical reconnection procedure, we continuously monitor the skin surface temperature of the flap with an IR camera. A fast and overall rewarming of the cooled down flap indicates that an adequate arterial inflow and venous drainage has been re-established. Thus, the thermal dynamics of the rewarming process, shown by its rate and change in thermal pattern, can be easily registered with the IR camera. (Figure 4)

The rapid appearance of a hot spot on the flap clearly indicates where the rewarming starts. If, for some reason, there is either a partial or total obstruction of arterial inflow, for example by kinking or external compression of the feeding vessels, this can be quickly registered with infrared thermography. During such an event, a poor rate and pattern of rewarming can immediately be detected from the infrared images. The changes in the thermal images are so rapid that they always preceded those registered by clinical observations, thereby permitting a rapid corrective response. In some cases, an additional (2nd.) recipient vein is also anastomosed to another vein to help improve venous drainage. An improvement in rate and pattern of rewarming of free DIEP flaps is often seen after an additional venous anastomosis is opened. After the successful reestablishment of blood circulation to the transferred flap, the flap is then modeled to form the correct shape of the new breast. Since the remodeling process requires the flap to be physically manipulated,

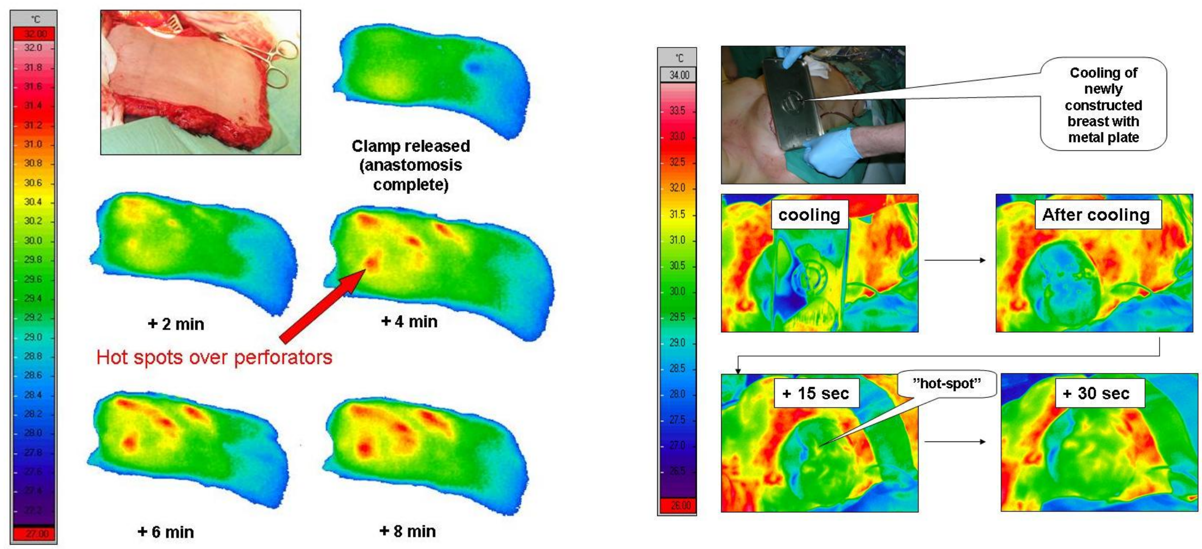

Fig. 4. Left Panel: A series of IR thermal images illustrating rewarming of a free DIEP flap following the successful completion of the microsurgical anastomotic procedure. Note the rapid appearance of hot spots. Right Panel: Final test at end of surgery. Cooling of the newly modeled breast with a metal plate at room temperature. Rapid return of warm spots indicates adequate perfusion.

there is always a risk of damaging or compromising the newly established blood supply. To ensure that circulation is not impaired during the modeling process; we continuously monitor the temperature of the flap. A compromised blood flow can easily and rapidly be detected from resultant changes in the thermal images.

Following the initial anastomotic procedure, as well as at various stages during the modeling process and at the end of the operation, we test that the reestablished blood supply is adequate by carrying out minor cold challenge tests (local skin cooling) either by lightly applying a cool metal surface to the skin for a few seconds or simply by washing the new flap with physiologic saline solution at room temperature. Both procedures cause a skin cooling which, if blood perfusion is adequate, is followed by a rapid appearance of hot spots as the flap spontaneously rewarms.

POST-OPERATIVE USE OF DIRT

Although intra-operative monitoring is of uttermost importance, in the post-operative phase, perfusion problems may occur as well. Flap monitoring in this phase is therefore necessary. DIRT has been shown to be a reliable, easy, and non-invasive method to monitor flap perfusion post-operatively (Figure 5). We employ cold challenges and recovery protocols routinely in the days following reconstructive surgery to ensure the new breast is adequately perfused. Our experiences with the technique are positive. In addition, patients find the infrared thermal images easy to understand which gives them extra reassurance in the days following their surgery

SUMMARY

The preoperative use of DIRT allows for a qualitative assessment of perforators to the DIEP flap providing valuable information that helps in planning and designing this flap. The intraoperative use of DIRT can provide the surgeon with valuable information on flap perfusion during free perforator flap surgery. The postoperative use of DIRT revealed that the perfusion of free DIEP flaps during the first postoperative week is a dynamic process. Although, not discussed in detail in this article, we have been able to show with DIRT that the perfusion of a newly transferred tissue flap has a stepwise progression at different tissue levels, each with its

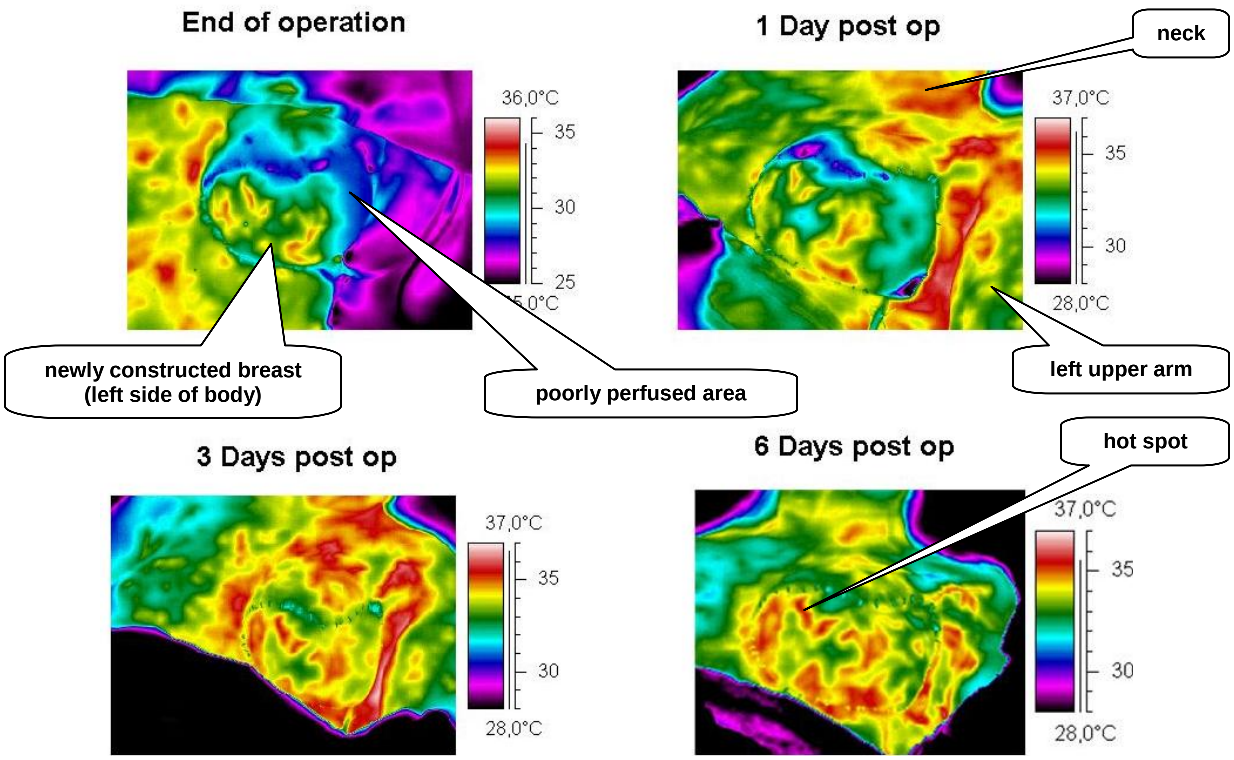

Fig.5. Reconstruction of left breast. Infrared thermal images showing the improvement in blood perfusion in a free DIEP flap at 1, 3 and 6 days after surgery. Note that part of the newly constructed breast is less well perfused at end of operation (indicated by blue area), but improves in the days following the operation (appearance of new hot spots).

own time sequence and with the midline as an area of resistance for circulation (see de Weerd et al 2009 for further details on this point).

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Associate Professor Sven Weum is a medical doctor studying for a Ph.D. at the Department of Radiology, University Hospital North Norway. He is an expert in medical imaging, especially in the use of Doppler ultrasound imaging, but also employs thermography in his studies.